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Utilisation of heat-treated ornamental stone processing waste as an addition to concretes to improve compressive strength and reduce chloride ion penetration

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HIGHLIGHTS

- The ornamental stone processing waste (OSPW) was heat treated at 1200 °C.
- Heat-treated ornamental stone processing waste (HTOSPW) presents pozzolanicity.
- Durability properties of concretes using HTOSPW were evaluated for the first time.
- 10% addition increased the mechanical strength and reduced chloride ion penetration.

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ABSTRACT

In the present study, the ornamental stone processing waste was heat treated at 1200 °C, with the goal of converting it into a pozzolan. At first, the treated waste characterisation was performed in order to assess its physical and chemical characteristics along with its pozzolanic activity. Then, concretes with 5% and 10% waste content were produced, and their compressive strength and chloride penetration resistance were evaluated. The heat-treated waste presented pozzolanic activity, and its addition into concrete mixtures provided an increase in compressive strength and reduction in chloride ion penetration; mainly in the mixtures with 10% addition.

1. Introduction

Raw material extraction and processing generate wastes that, in most cases, are environmental liabilities. Aiming at solving this issue, many studies demonstrate the applicability of different wastes, by giving them a more valuable end-use than disposal. Among these wastes, the use of fly ash [1–5] and silica fume [6–10] can be highlighted; these are used consistently worldwide in cementitious matrixes, and can now be considered as products. They are applied as pozzolans, which react chemically with alkaline compounds produced during the hydration of cement, producing calcium silicate hydrate (C-S-H). Consequently, pozzolans are considered materials with good performance that provide improvement to the properties of a cementitious matrix.

Ornamental stone processing waste (OSPW) is a waste that has been studied by different authors, regarding its use in cementitious [11–14], ceramic [15–18] and bituminous [19–21] matrixes. In 2013, the worldwide production of ornamental stones was 123.5 Mt [22]. From its extraction to trading, the amount of waste produced can be up to 40% of the total volume of stone extracted [17]. The amount of waste generated in the processing stage alone (cutting and polishing) can be 20 to 25% of the total volume of the stone block [17]; even up to 30% [23]. Thus, the annual stone extraction of 10 Mt in Brazil (the fourth largest producer worldwide of ornamental stones) [22] produced approximately 3 Mt of waste in 2013 – more than the double of fly ash currently used in blended cement production (1.44 Mt) [24].

When applied to cementitious matrixes (CM), the OSPW acts as an inert filler material producing a pore-filling effect [13]. Thus, prior to its addition to cement-based mortars, some authors [25–27] performed a heat treatment (HT) on this waste, at temperatures ranging from 700 [25,26] to 1200 °C [27], with the intent of improving its physical-chemical properties, changing its state from crystalline to amorphous, and converting it into a pozzolan. The treated waste appears to have potential for use in concrete

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structures, and the mechanical properties of mortars produced with the waste after HT have been analysed [25–27]. However, little is known of its influence on the mechanical and durability properties of concrete, especially when the concrete is exposed to an aggressive maritime environment.

Furthermore, if the HT of this waste produces an improved material for using in concrete production, it can provide a solution to the pozzolans scarcity in some regions of Brazil. In the region where this study was conducted (Espírito Santo – the largest producer and exporter nationwide of ornamental stones [28]), the fly ash transport distance is over 2000 km [29].

The present study performed a HT on the waste at 1200 °C, the temperature that achieved the best pozzolanic activity combined with the easiest production process for this material [27]. After the HT, the material was milled and assessed according to its physical and chemical properties, and named as heat treated ornamental stone processing waste (HTOSPW). Then it was used as a possible pozzolanic addition in the production of concrete mixtures, with contents of 5 and 10% by cement mass. The mixtures were evaluated according to their mechanical properties, and a durability analysis was performed according to different tests, focusing on chloride ion penetration.

2. Experimental program

2.1. Materials

High early-strength Portland cement (CPV-ARI) was used in this study. Since mineral additions in cement composition can interfere with the test results, this cement was used as it is the commercially available cement in Brazil with the lowest percentage of additions (up to 5% limestone powder). Grain size distribution, and physical and chemical characteristics of the cement, can be seen in Fig. 1, Tables 1 and 2, respectively. Natural white quartz sand and granitic coarse aggregate were also used in the mixtures. The fine aggregate had maximum grain size of 2.4 mm and specific gravity 2.57. The coarse aggregate had maximum grain size of 19 mm and specific gravity 2.77.

The OSPW was obtained from a marble factory in the Espírito Santo district, in Brazil, after the cutting and polishing of stone. The waste was kiln dried at 100 ± 5 °C for humidity removal (Fig. 2a). Next, it was subjected to gradual HT for approximately 6 h until reaching 1200 °C, remaining at this temperature for 2 h. This HT process was evaluated in the study of Uliana et al. [27] in which the temperature of 1200 °C was selected, and thus is used as reference in this work. Due to HT, the waste coalesced into a solid with vitreous appearance, as can be seen in Fig. 2b.

Then, the material was milled in a vibratory disc mill (Fig. 2c) for the time required to reach the fineness criterion for pozzolanic material as defined in NBR 12653 [30]. According to this standard, the maximum percentage of material retained should be 20% on sieve #325 (45 µm). After the milling process, the material presented a light grey colour (Fig. 2d).

Table 1
Physical characteristics of HTOSPW and cement.

Tests	Physical requirements (NBR 12653)	HTOSPW	Cement
Retained on sieve #400 (%)	–	–	2.2
Retained on sieve #325 (%)	<20%	9.57	–
Retained on sieve #200 (%)	–	1.16	–
Density (g/cm^3)	–	2.45	3.09
Blaine specific surface area (cm^2/g)	–	6890	4751
Pozzolanic activity with lime (MPa)	>6 MPa	7.24	–
Pozzolanic activity cement (%)	>90%	103	–

The physical and chemical characterisation of the HTOSPW was performed to verify its pozzolanic activity after HT. Brazilian standard NBR 12653 [30] requires the following tests to determine the pozzolanic activity: pozzolanic activity with lime [31], with cement [32], material retained on sieve #325 [33], and chemical composition by X-ray fluorescence (XRF). Furthermore, tests for grain size distribution analysis were performed by laser diffraction, Blaine specific surface area [34], density [35] and material retained on sieve #200 [36].

The grain size distribution of the HTOSPW was assessed by laser diffraction, and the results are presented in Fig. 1. The values of D10, D50 and D90 were 1.29, 8.17 and 48.99 µm, respectively, showing that the HTOSPW is an extremely fine material. The D10 (D50 or D90) criterion means that 10% (50% or 90%) of the particles have a diameter lower than this value. In Fig. 1, it can also be noted that the cement has a more uniform distribution than HTOSPW, which has a more continuous distribution. This continuous distribution can contribute to a higher compactness and pore-filling of the cementitious matrix when HTOSPW is added.

It can be noted in Table 1 that all the physical requirements for classifying HTOSPW as a material with pozzolanic activity, according to NBR 12653 [30] were satisfied. It presented 9.57% of retained material on sieve #325 (45 µm), and 1.16% of retained material on sieve #200 (75 µm), values close to those presented in Fig. 1: 11.83% of diameter 45 µm and 3.12% of diameter 75 µm. Furthermore, the HTOSPW presented a higher Blaine value than cement: 6870 cm^2/g, whereas the value for cement was 4751 cm^2/g. It was also higher than common Blaine values for fly ash, determined in other studies [37–39]. The Blaine value confirms the size distribution of Fig. 1, given that D50 was 8.17 and 13.75 µm, for HTOSPW and cement, respectively.

According to Neville and Brookes [40], pozzolans present densities varying from 1.9 to 2.4 g/cm^3, which are lower than the characteristic value of cements (3.15 g/cm^3). The HTOSPW presented a density of 2.45 g/cm^3, being close to the characteristic values of pozzolans. Additionally, the criteria for pozzolanic activity with lime and cement were satisfied (Table 1).

Table 2 presents the chemical composition of the HTOSPW by XRF. It can be noted that HTOSPW is a silico-aluminous material, characteristic of pozzolans. It presents a chemical composition similar to that of widely known pozzolans, such as metakaolin [9,41] and fly ash [42,43], especially when compared the contents of silica (SiO_2) and alumina (Al_2O_3).

Furthermore, from Table 3 it can be verified that the HTOSPW also fulfilled the chemical criteria for pozzolanic activity according to NBR 12653 [30] – except the criterion of available alkalis in Na_2O_{eq}, which exceeded by 0.71% the maximum allowed. Nevertheless, the alkali percentage is not directly related to the pozzolanic

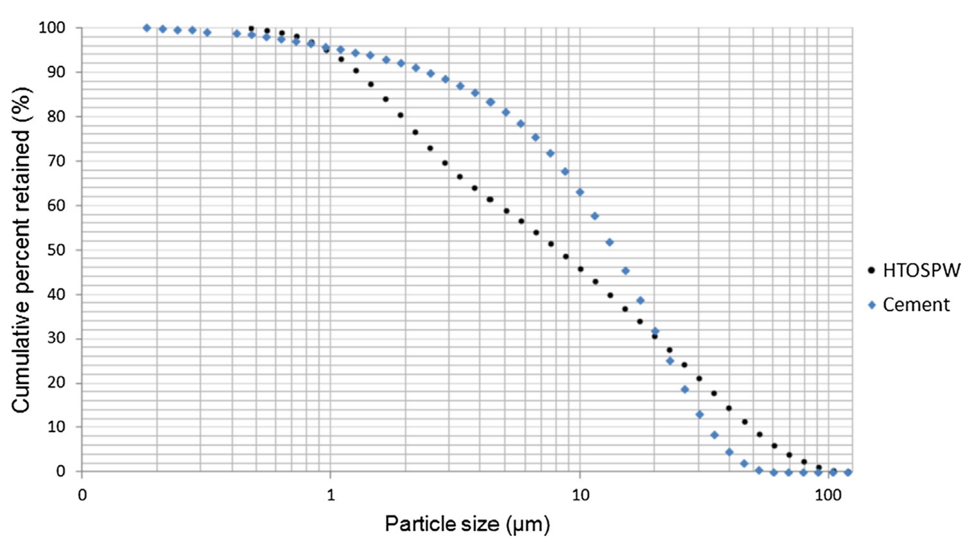

Fig. 1. Grain size distribution of HTOSPW and cement.